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The Effects of Tyre Size on Soil Deformation and Soil Bulk Density Changes

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Abstract. *The selection of appropriate tyre size and inflation pressure for a particular load and soil condition are crucial to minimising soil compaction and ensuring soil sustainability. The purpose of this study was to investigate the changes in soil bulk density from soil deformation data, produced by a selected range of combine-harvester tyres, inflated to the recommended inflation pressures, and at high axle load (10.5 tonnes) to provide a valuable indicator for tyre selection. Results showed that the initial soil strength was the main factor influencing soil deformation and soil bulk density changes beneath the tyres. In addition, increased tyre size and low inflation pressure reduced both soil deformation and the resultant increase in soil bulk density. The increases in soil bulk density after one passage of the tyres over the soil were approximately 25% for the low bulk density soil (1.20 g cm^{-3}) and between 2.3% and 5% for the high bulk density soil (1.60 g cm^{-3}). The advantage of increasing tyre size and lowering inflation pressure was also reflected in the results obtained from penetrometer resistance: at the centre of the wheeling, the tyre with the highest inflation pressure (2.5 bar) gave a significantly higher increase in penetration resistance compared with the tyres with lower inflation pressures (2.2 bar and 1.9 bar). Linear relationships between drop-cone penetration and maximum rut depth were established; these data were subsequently related to those obtained from penetration resistance and initial soil bulk density; therefore, the increase in soil bulk density induced after driving a tyre over the soil can be determined for various tyre configurations and initial soil conditions.*

Keywords. Soil deformation, tyre inflation pressure, soil bulk density, soil penetration resistance, drop cone penetrometer

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Introduction

Efficient mechanisation in agriculture is a major factor underlying high productivity: larger machinery is often related with timeliness, higher work rates, and lower labour requirements. The drawback of it is that larger machinery usually means increased machinery weight which increases the danger of soil compaction (Raper, 2005). Soil compaction affects the physical, chemical, and biological properties of soils and is one of the main causes of agricultural soil degradation (Hakansson and Voorhees, 1998). Its alleviation is usually costly in terms of the energy and power that the process of soil loosening requires. Generally, an increase in tyre size is accompanied by a decrease in tyre inflation pressure to support a given axle load. This also provides improved tractive performance and reduced soil deformation since the average soil contact pressure under the tyre is approximately equal to the inflation pressure plus carcass stiffness (Plackett *et al*., 1987, and Misiewicz *et al*., 2008). Soil compression behaviour is also related to the initial soil bulk density which is one of the most used measures of soil compaction. Low bulk density soils can suffer from low strength and hence greater deformation and compaction, compared with those with high bulk density.

The aim of this work was to determine the change in soil bulk density from soil deformation data for a selected range of tyres, inflated to the recommended inflation pressures, and at fixed axle load (10.5 tonnes) by extending the graphical representation of the data reported in earlier investigations (Stranks, 2006, Ansorge and Godwin, 2007 & 2008). This would provide a valuable indicator for tyre selection.

Methodology

The investigation was conducted in a soil bin with uniform soil conditions at the Soil Dynamics Laboratory at Cranfield University at Silsoe (UK). Soil bin characteristics were described in detail by Earl and Alexandrou (2001). It is 22 m long, 1.7 m wide and 1 m deep. The soil used was a sandy loam *Cottenham series* (King, 1969) with 66% sand, 17% silt, and 17% clay, which was maintained at approximately 10% (g g^{-1}) moisture content. Two different soil bulk densities were used: low (1.20 g cm^{-3}) and high (1.60 g cm^{-3}). Three different combine-harvester tyres manufactured by *Continental*® were used during this study (**Table 1**). The tyres were operated at a speed of 1 m s^{-1} in a single wheel test rig (Ansorge and Godwin, 2007 & 2008) at the recommended inflation pressure according to the manufacturer's specifications for the working load (10.5 tonnes). The tyres will be referred to in the form of section width (mm)/load (t)/inflation pressure (bar); e.g. 900/10.5 t/2.2 b.

Table 1: Tyre specification

Tyre	Section Width (mm)	Aspect Ratio	Rim Diameter (in)	Tyre Diameter (mm)	Lug Height (mm)	Tyre Construction	Inflation Pressure (bar)
1	680	85	32	1969	42	Radial	2.2
2	800	65	32	1853	58	Radial	2.5
3	900	65	32	1983	55	Radial	1.9

A technique developed by Ansorge and Godwin (2007) to determine soil deformation (strain) and soil bulk density changes based upon the principles outlined by Trein (1995) was used in this study. This technique consisted of using talcum powder and placing the soil in the soil bin in layers. During the preparation of the soil bin, talcum stripes were placed every 100 mm of soil (i.e. between soil layers) after rolling and wetting the soil to allow the talcum powder to stick to the soil on top of the layer. A total of 7 layers with talcum powder were used throughout the soil profile; each soil layer had 14 talcum powder lines of 200 mm long and 6 mm wide across the width of the soil bin, each one separated vertically and horizontally by 100 mm. These talcum powder marks were put in three positions along the soil bin with the first one, on one end of the soil bin, being the control position where no wheel was driven over so as to use it as base for comparison. To be able to compare the tyres, the vertical displacement in each layer was calculated by subtracting the mean vertical coordinate (taken from the 4 central points) of the control from the final talcum powder position (after driving the tyre over the soil). This mean soil vertical displacement for any given depth was then plotted against depth to produce the diagram shown in **Figure 1.** Linear regression lines were subsequently fitted to this diagram; they indicate a constant increase in dry bulk density with depth whereby the reciprocal of the slope is equal to the percentage increase in dry bulk density as suggested by Ansorge and Godwin (2007 & 2008). This value can be used to compare different tyre configurations (Ansorge *et al*., 2007). Following Stranks (2006), the increase in dry bulk density was plotted against the initial soil bulk density (i.e. before driving the tyres over the soil) for each one of the tyre configurations used in this study; thereby, extending the graphical relationships reported in previous investigations. Soil penetration resistance and drop cone penetration (Godwin *et al*., 1991) were also measured. These data were subsequently linked to both the calculated increase in dry bulk density and the initial soil density to aid the estimation of the increase in soil bulk density after driving a tyre over the soil in these conditions. Similarly, drop cone penetration data were linked to measurements of rut dimensions (i.e. maximum depth) and the expected increase in dry bulk density. A statistical analysis was undertaken using GenStat Release 10.1 (2007) and involved analysis of variance (ANOVA) and least significant differences (LSD) to compare means. A 5% probability level was used ($p < 0.05$).

Results and discussion

Figure 1 shows soil vertical displacement plotted against depth for the selected range of tyres and soil conditions used in this study. Results obtained by Ansorge and Godwin (2007 & 2008) for a medium bearing capacity soil ($\gamma = 1.38$ g cm^{-3}) are also presented in **Figure 1** to allow comparisons to be made for a wider range of soil conditions. As shown in the diagram below, soil deformation for all tyres decreases progressively from the soil surface to a depth of approximately 700 mm.

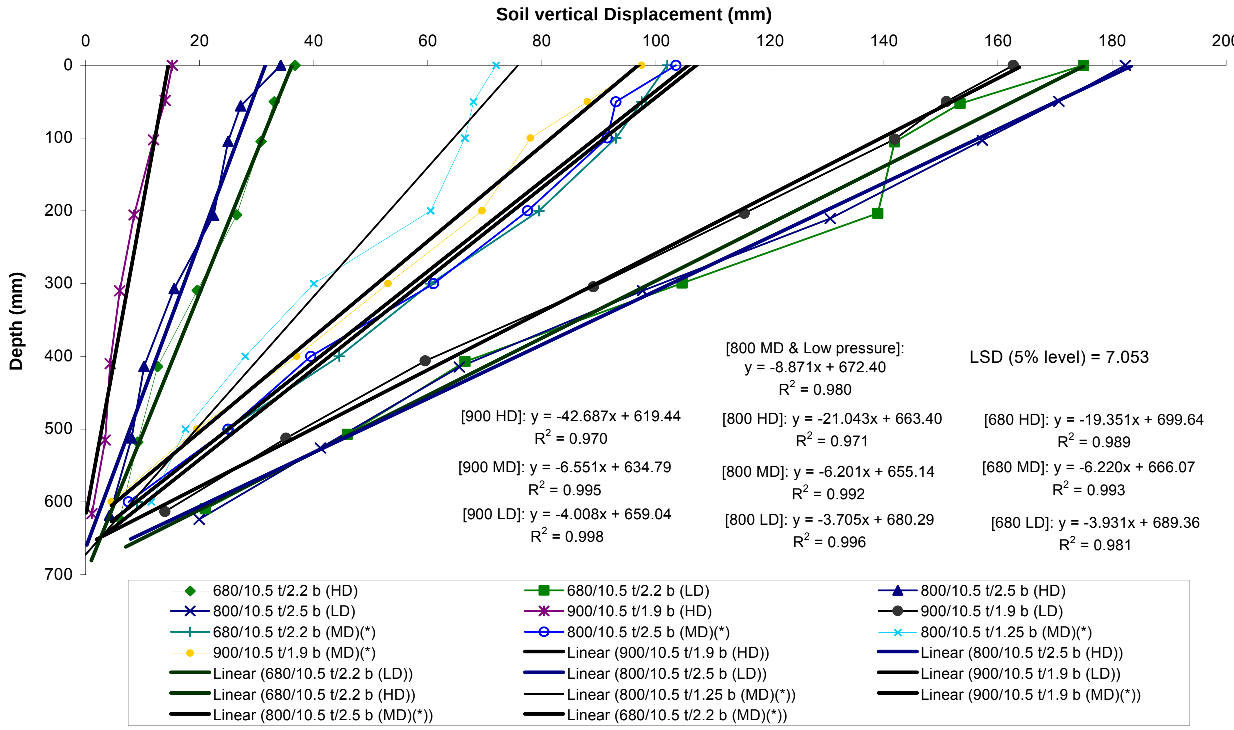

Figure 1: Mean soil vertical displacement vs. depth for the three different tyres and soil conditions used in this study (LD: low bulk density – $\gamma = 1.20$ g cm^{-3}, MD: medium bulk density – $\gamma = 1.38$ g cm^{-3}, and HD: high bulk density – $\gamma = 1.60$ g cm^{-3}). [Note: the tyres are referred to in the form of section width (mm)/load (t)/inflation pressure (bar). Data for $\gamma = 1.38$ g cm^{-3} from Ansorge and Godwin (2007 & 2008)].

The statistical analysis revealed that there were significant differences with respect to the tyres ($p = 0.001$) but there were not for the interaction between the tyres and soil condition ($p = 0.393$). This indicates that on both soil conditions (low and high soil bulk density), all tyres produced significant soil deformation compared with the control (undisturbed soil profile) but the amount of soil deformation produced by each individual tyre differed from each other on a given soil condition when they were used at the manufacturer's recommended inflation pressure (**Table 1**) for the working load (10.5 t). In fact, the 900 mm section width tyre caused always the least soil vertical displacement on both soil conditions being significantly different ($p < 0.001$) from both the 680 mm and the 800 mm section width tyres. This was particularly evident on the high bearing capacity soil where soil deformation caused by the 900/10.5 t/1.9 b (HD) was just under 50% of that caused by the 800/10.5 t/2.5 b (HD) and the 680/10.5 t/2.2 b (HD). On the softer soil, however, soil deformation caused by all tyres was similar as can be seen from the slope of the regression lines in **Figure 1**. These results can be attributable to a greater contact patch area (i.e. larger diameter and section width) and lower inflation pressure of the 900 mm section tyre compared with the 680 mm and the 800 mm section tyres respectively.

Previous investigations by Ansorge and Godwin (2007 & 2008) had also demonstrated the influence of tyre inflation pressure on soil deformation finding that the same 800 mm section width tyre loaded to 10.5 t on a medium bearing capacity soil (γ = 1.38 g cm^{-3}) and using half the recommended inflation pressure (1.25 bar) produced significantly less soil deformation ($p < 0.0001$), hence, compaction, than the same tyre inflated to 2.5 bar as shown in **Figure 1.** Vertical displacement diagrams (**Figure 2**) help to understand the response of the soil when it is subjected to stress. The length of the arrows indicates the magnitude of the displacement whereas the direction the arrows are pointing in indicates the direction of the displacement. Ageikin (1987) suggested that soil deformation by a wheel may be subdivided into three types: vertical and lateral displacement, and displacement in the direction of motion. Unfortunately, the method used in this work only allows for measurements in 2D. Further research by Ansorge and Godwin (2008) showed that the lateral movement of soil underneath self-propelled combine-harvester tyres on medium soil conditions (γ = 1.38 g cm^{-3}) was limited to the first 150 mm from the surface. More research into the lateral displacement of soil beneath self-propelled combine-harvester tyres is needed for the other two soil conditions used in this investigation.

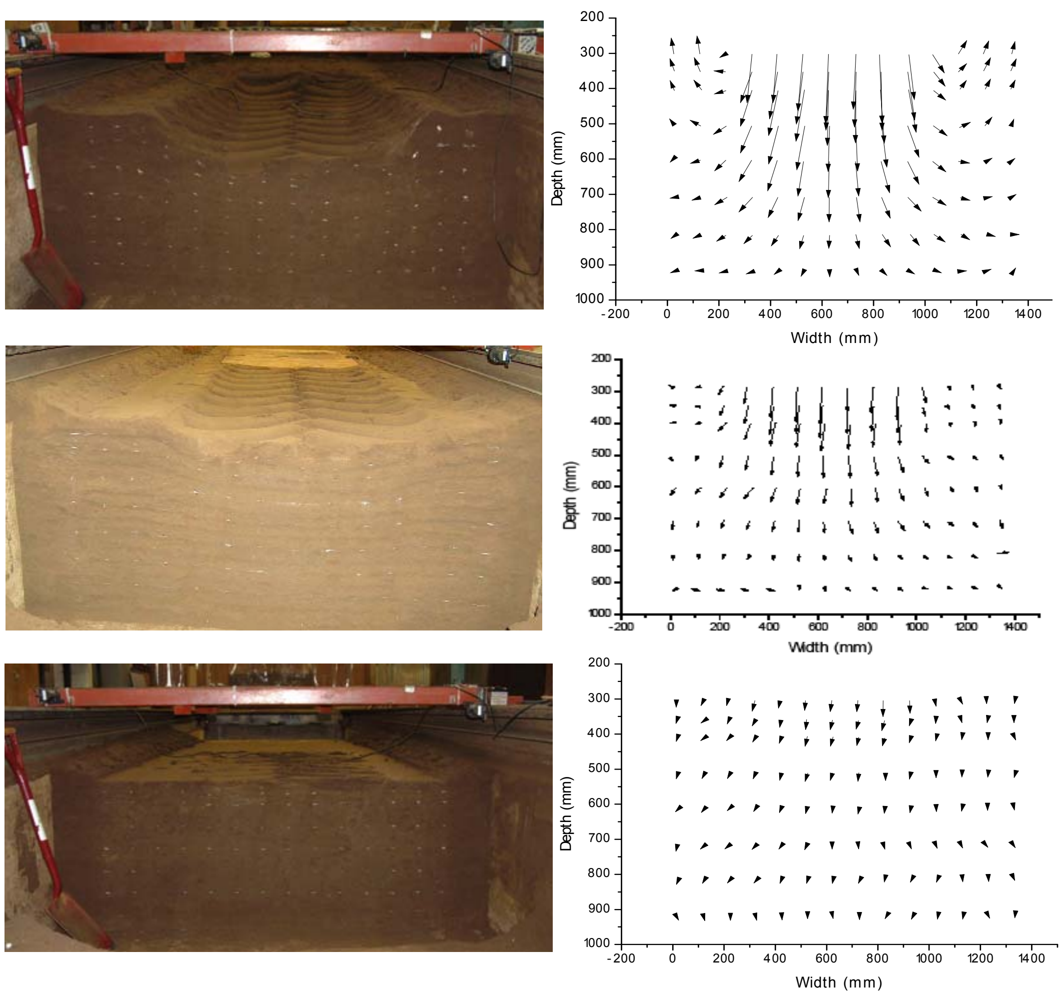

Figure 2: Soil vertical displacement diagrams after one passage of the 900/10.5 t/1.9 b. [Top: low bulk density soil (γ = 1.20 g cm^{-3}); middle: medium bulk density soil (γ = 1.38 g cm^{-3}); bottom: high bulk density soil (γ = 1.60 g cm^{-3})].

On the low bearing capacity soil, the lateral soil displacement at depth may be caused by the depth of the soil bin which might have impeded further vertical displacement of soil near the floor of the tank. The facility to use a deeper and wider soil bin is now available at Cranfield University at Silsoe (Godwin *et al*., 2006). On the medium bearing capacity soil, however, the arrows at 920 mm depth pointing mostly to the right are due to the position of the talcum powder board not being accurately placed in the centre of the soil bin. The interaction between tyres and soil displacement in the different layers below the soil surface showed that there were significant differences ($p < 0.001$) for the different tyres. This is mainly because the 900/10.5 t/1.9 b consistently showed significant differences with the other two tyres on both soil conditions. In addition, on the softer soil, the 800/10.5 t/2.5 b produced the greatest displacement in the uppermost layers (0 – 400 mm) and particularly between 0 – 100 mm deep. Below 400 mm, the regression lines for the 680/10.5t/2.2 b and the 800/10.5 t/2.5 b converged; therefore, producing the same effect at depth. On the harder soil, no differences were recorded for these two tyres; this is also shown on the similarity of slope of the regression lines. The graphical relationship between the initial soil bulk density and its percentage increase produced after driving a tyre over the soil reported by Stranks (2006) was extended to a larger number of tyre sizes and loads as shown in **Figure 3**.

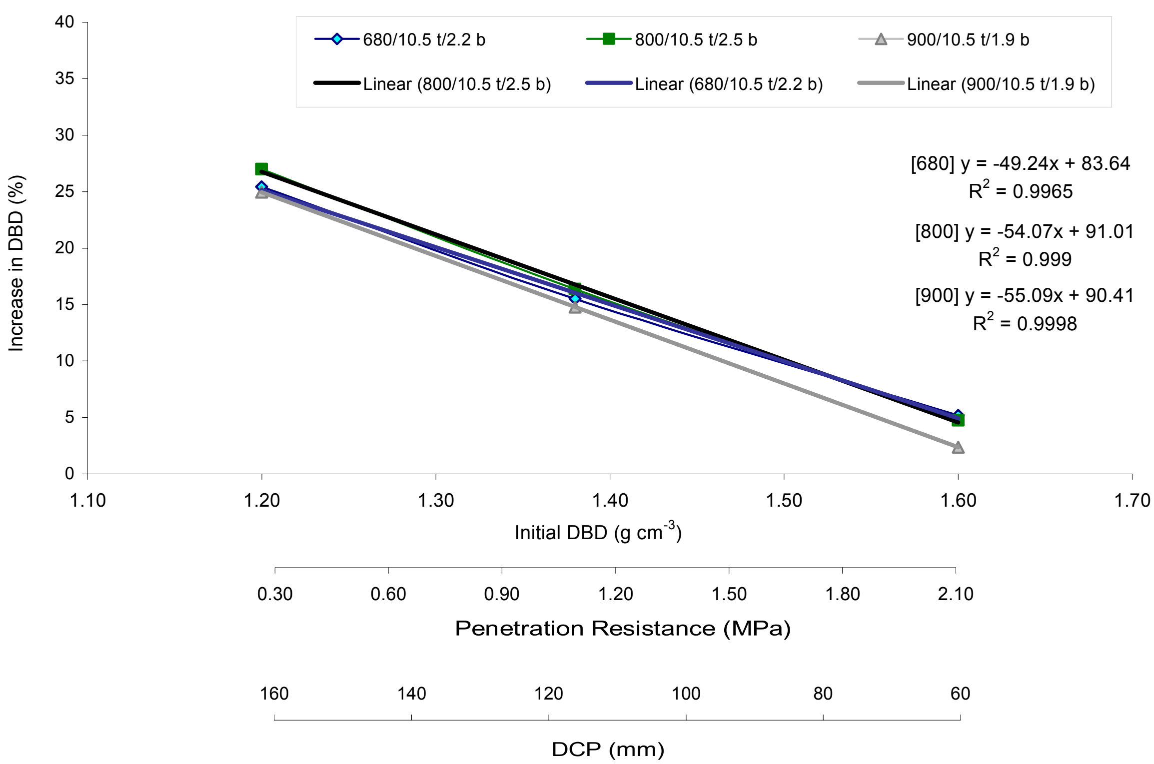

Figure 3: Percentage increase in dry bulk density (DBD) as a function of initial soil bulk density, penetration resistance, and drop cone penetration (DCP) for various tyres configurations. [Data for γ = 1.38 g cm^{-3} from Ansorge and Godwin (2007 & 2008)].

As shown in **Figure 3**, regardless of the tyre, the increase in soil bulk density decreases progressively as the initial soil bulk density increases. The 900 section width tyre appears to be marginally better compared with the 680 mm and the 800 mm section tyres, especially, when the initial soil bulk density is higher than 1.30 g cm^{-3}. The R^2 values encountered clearly reflect linear relationships for all the tyres configurations. When comparing the 680/10.5 t/2.2 b and the 800/10.5 t/2.5 b, both tyres showed a similar performance in terms of soil density changes over the range of initial soil conditions. Although the 680/10.5 t/2.2 b has a smaller section width than the 800/10.5 t/2.5 b, the contact patch areas remain similar for both tyres, hence soil deformation is also similar. The smaller section width of the former tyre is compensated by a larger section height and lower inflation pressure than the 800/10.5 t/2.5 b.

Interestingly, and according to the work done by Stranks (2006), smaller tyres (500/60-22.5; 700/50-26.4; and 800/40-26.4) loaded to 4.5 t were shown to have an exponential increase in soil density change as the soil becomes softer whereas larger tyres (as those used in this investigation) loaded to 10.5 t appear to be linear with decreasing soil density. In addition, as the tyre inflation pressure decreases, the percentage increase in dry bulk density tends to decrease significantly. This is more obvious on the medium and low bearing capacity soil conditions.

Overall, the mean increases in soil bulk density were 25.7% for the low density soil and between 2.3% and 5% for the high density soil. Ansorge and Godwin (2007) found a mean increase in soil bulk density of 17.5% using the same tyre configurations but on a medium bearing capacity soil (γ = 1.38 g cm^{-3}).

The results shown in **Figures 1** and **3** highlight the influence that soil strength (i.e. initial soil bulk density) can have upon soil deformation, and ultimately, soil compaction. Therefore, assessing soil strength becomes particularly important prior to undertaking field operations; this would enable both the prediction of potential damage to the soil and the selection of an adequate running gear. Equally, knowing the strength of the soil at any particular time would help to adapt the machinery (e.g. lowering the tyre inflation pressure) so as to minimise soil compaction. Assessment of soil strength can be done by means of a drop cone penetrometer (Godwin *et al*., 1991).

Figure 4 shows the relationship between drop cone penetration, maximum rut depth, and the expected increase in dry bulk density after driving the 900 section width tyre over the soil. For uniform soil conditions, this relationship appears to be linear. The same relationship was proven for all the tyres and soil conditions used in this investigation.

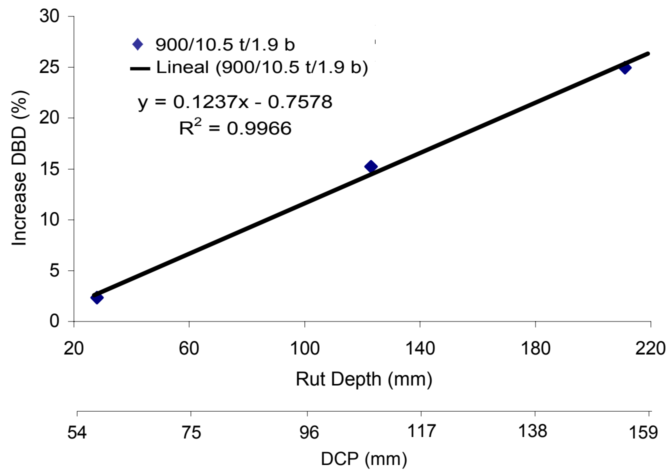

Figure 4: Relationship between drop cone penetration (DCP), maximum rut depth, and expected increase in soil bulk density (DBD) when the 900/10.5 t/1.9 b tyre is driven over the soil. [Maximum rut depth was measured at the centre of the wheeling].

The results of penetration resistance obtained before and after one passage of the tyres over the soil for the high and the low bulk density soil conditions respectively are shown in **Figure 5**. As expected, significant differences ($p < 0.001$) in penetration resistance were obtained before and after one passage of the tyres over the soil. However, the interaction between the tyres and penetration resistance before and after the running showed no significant differences between the tyres indicating that on average and after one passage, all tyres produced a similar increase in penetration resistance ($p = 0.088$) when they were used on the high and low bulk density soils respectively. The initial soil condition appeared to be the main factor influencing the magnitude in the change in soil penetration resistance; in fact, after one passage of the tyres, mean penetration resistance increased approximately three times in the low bulk density soil whereas it was 5% in the high bulk density soil.

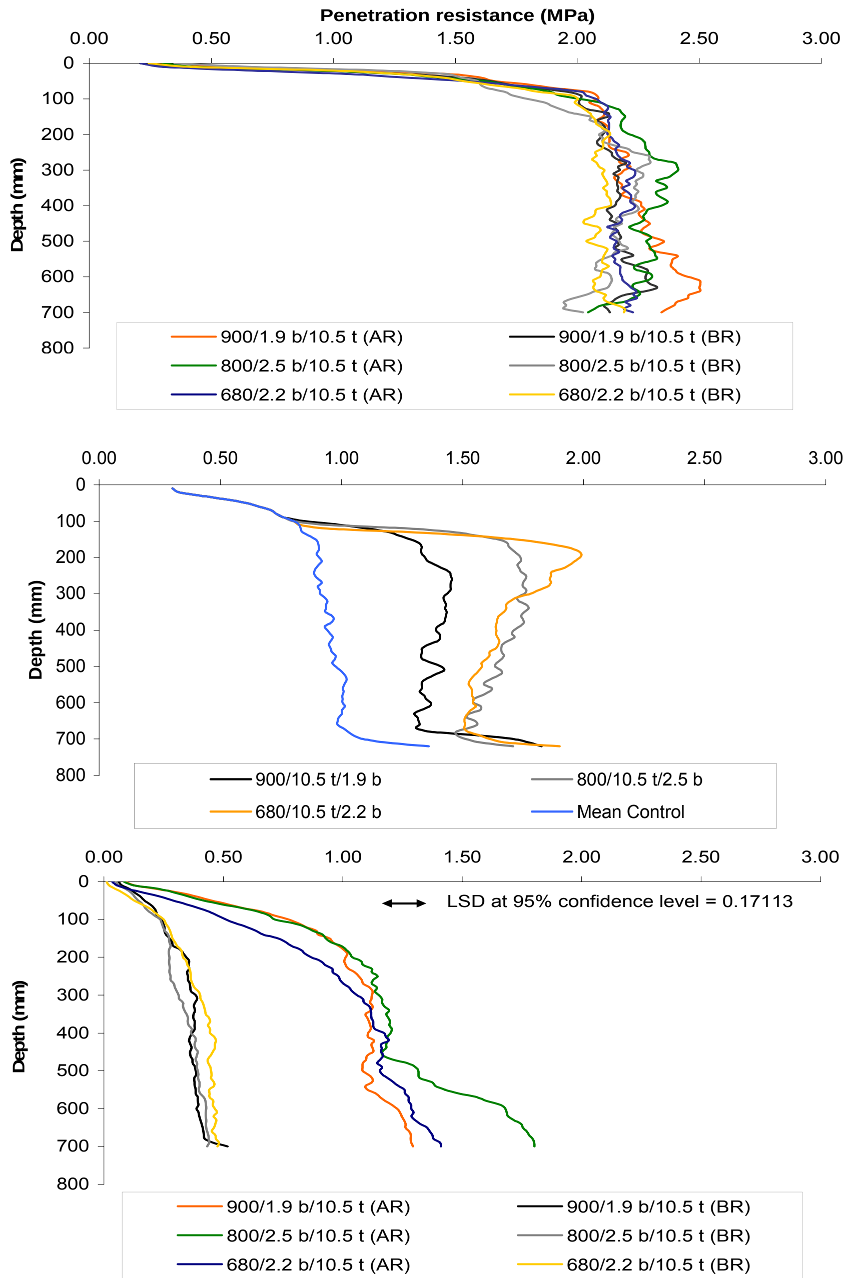

Figure 5: Soil penetration resistance before (BR) and after (AR) running the tyres over the soil. [Top: high bulk density soil (γ = 1.60 g cm^{-3}); middle: medium bulk density soil (γ = 1.38 g cm^{-3}); bottom: low bulk density soil (γ = 1.20 g cm^{-3}). Data for γ = 1.38 g cm^{-3} from Ansorge and Godwin (2007 & 2008)].

It is interesting to note that the 900/10.5 t/1.9 b produced a slightly greater mean penetration resistance compared with the 680/10.5 t/2.2 b (1.5752 vs. 15093 MPa) which may be attributed to the larger section width and the way the readings were averaged across the whole width of the soil bin.

This difference was, however, not significant (LSD [5% level] = 0.08578). The 800/10.5 t/2.5 b had a mean penetration resistance of 1.6402 MPa; this indicates a small difference compared with the 680/10.5 t/2.2 b for the same LSD value. It seems that a greater inflation pressure may have influenced this result since the contact patch areas were similar between these two tyres. This value is also greater than that of the 900/10.5 t/1.9 b which has a larger section width but lower inflation pressure. Finally, it was observed that for all the tyres; mean penetration resistance increased significantly ($p < 0.001$) towards the centre line of the wheel rut with the maximum value being recorded at the centre of the wheeling. In this respect, the 800/10.5 t/2.5 b had a significantly higher penetration resistance than the 680/10.5 t/2.2 b and the 900/10.5 t/1.9 b with mean values of 1.9648, 1.7164, and 1.7863 MPa respectively (LSD [5% level] = 0.11687).

Conclusions

The main conclusions coming from this research are highlighted below.

1. The initial soil condition (i.e. soil strength) was the main factor influencing final soil deformation, the increase in soil bulk density, rut dimensions, and the increase in penetration resistance, under the prevailing experimental conditions.
2. The increases in soil bulk density, calculated from soil deformation data for all the tyre configurations, were 25% for the low and between 2.3% and 5.2% for the high bulk density soils.
3. The 900 mm section tyre produced the lowest soil deformation, and therefore, the lowest increase in soil bulk density compared with the 680 mm and the 800 mm section tyres for all soil conditions; i.e. low, medium, and high bulk density soils. This can be attributable to a larger contact patch area and a lower inflation pressure of the 900 mm section tyre compared with the other two tyres.
4. The 680 mm and the 900 mm section tyres produced a lower increase in penetration resistance than the 800 mm section tyre. Lower inflation pressure and a greater contact patch area of the 900 and the 680 mm section tyres, compared to the 800 mm section, significantly reduced soil penetration resistance at the centre of the wheeling.
5. The increase in penetration resistance outside the wheeling was due to displacement of soil in the horizontal direction, particularly on the low bulk density soil, which was recorded in the displacement diagrams.
6. Linear relationships were established between drop cone penetration and maximum rut depth for all the tyre configurations used in this research. These data can be used to calculate the expected increase in soil bulk density for individual tyre configurations.

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